Lasers for Deep Space Optical Communications

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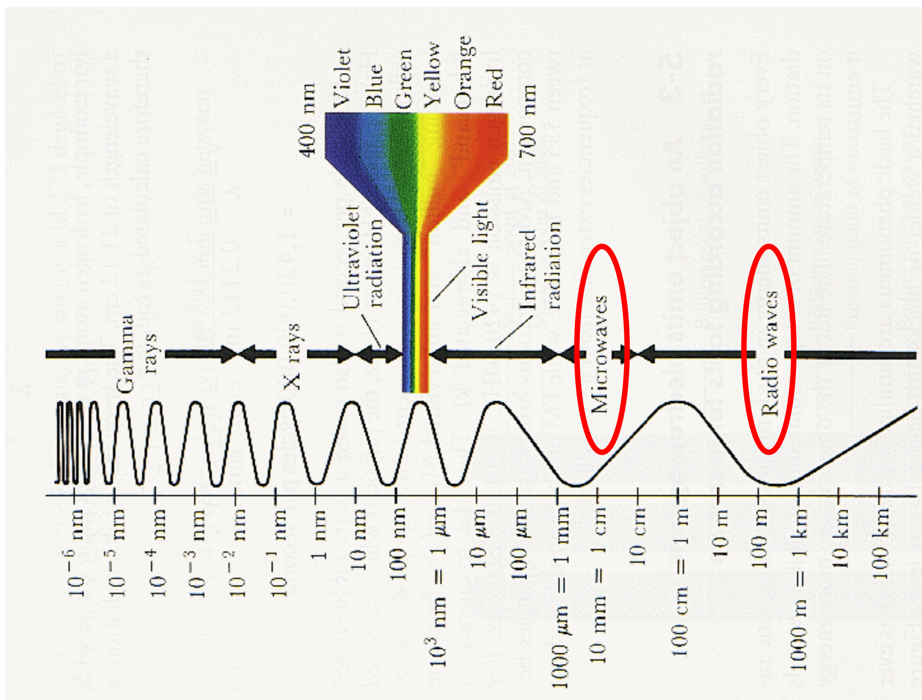
Outline

- Background
  - Why do we want to change to lasers from radio transmitters?
  - How lasers work – history of laser, types of lasers
  - Applications for lasers
- Lasers for telecom
- Deep Space Optical Communications (DSOC) lasers
- Downlink laser
  - Design
  - Candidate results
- Uplink laser
  - Design
  - Candidate systems and preliminary test results
- Future work
- Summary

Motivation

- Why do we want to change to lasers from radio transmitters?
  - Higher carrier frequency (shorter wavelength)
    - Supports higher modulation rates



Laser wavelengths

$$c = f\,\lambda$$

c = speed of light
f = frequency
λ = wavelength

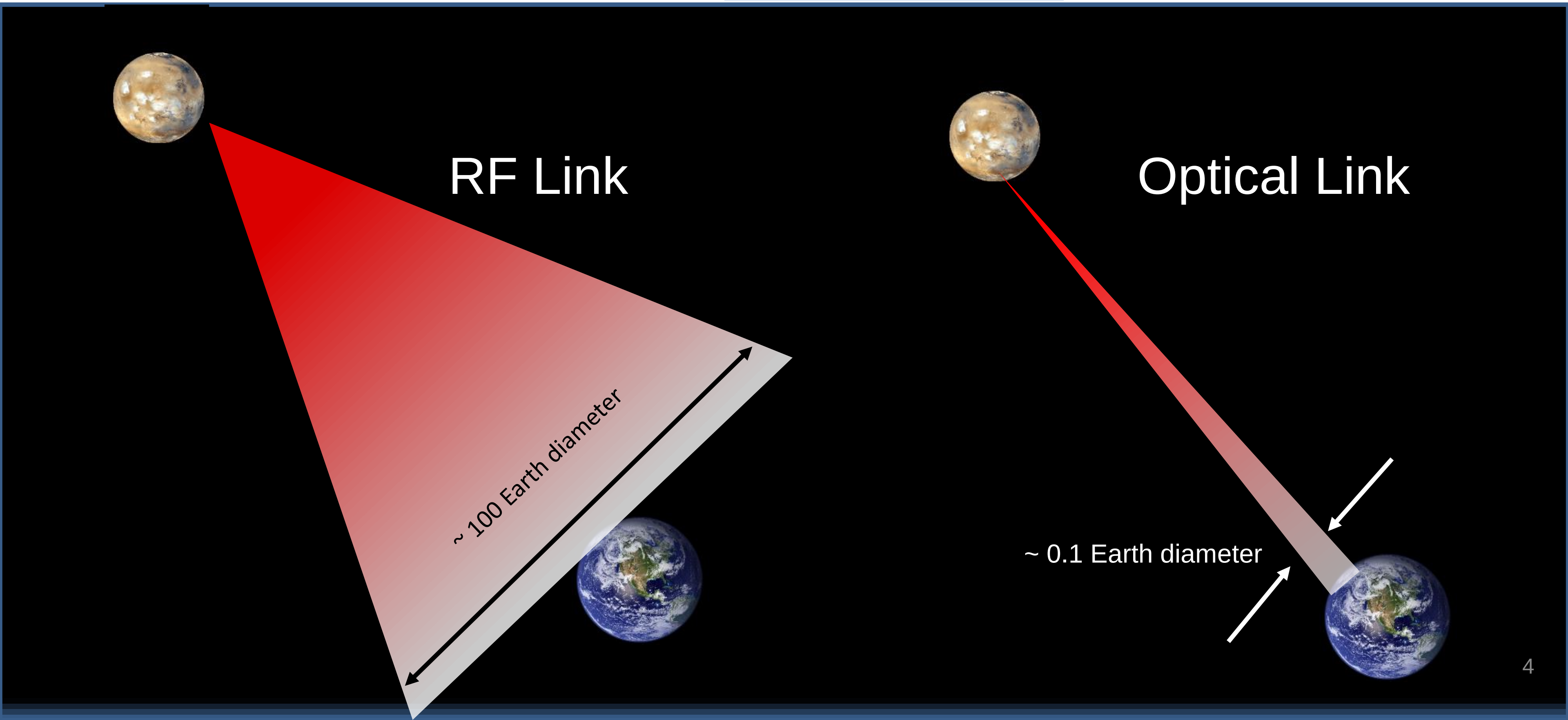
$\Rightarrow$ Higher data rate

Motivation

- Why do we want to change to lasers from radio transmitters?
  - Higher carrier frequency (shorter wavelength)
    - Less divergence

    $\Rightarrow$ Increased power efficiency

$$\theta = M^2 \frac{\lambda}{\pi\omega}$$



Motivation

- Why do we want to change to lasers from radio transmitters?
  - Leverage industrial development
    - Telecom has moved to laser comm with fiber optic based transmitters
    - High power laser development for machining

    $\Longrightarrow$ robust, compact and reliable lasers

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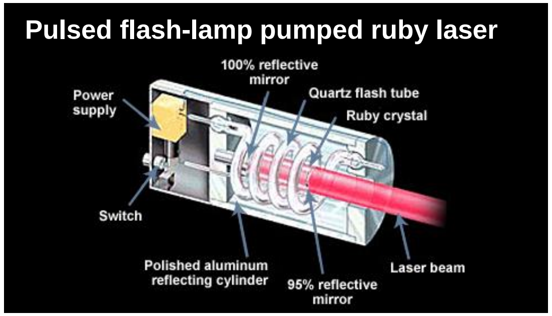
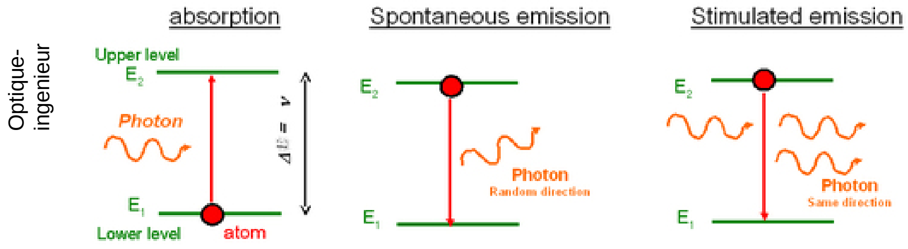
Laser tutorial

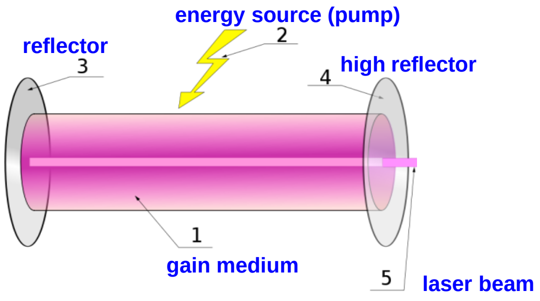
- History of laser
  - *Theodore Maiman (Hughes Research Lab.), having invented the first working laser ("optical maser") on May 16, 1960, described it as "a solution looking for a problem" because so few appreciated its manifold possibilities.*



$\Rightarrow$ Solid state crystal laser, gas lasers, diode laser, quantum well lasers, fiber amplifier, dye, FEL…

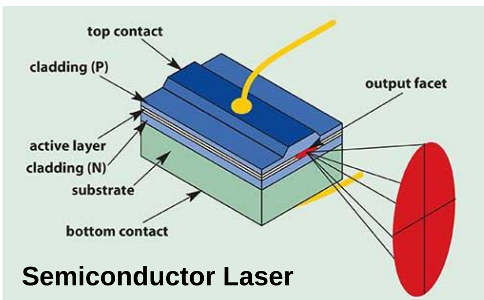
- How lasers work
  - Laser needs:
    - Gain medium to produce stimulated emission
    - Resonator that amplifies light

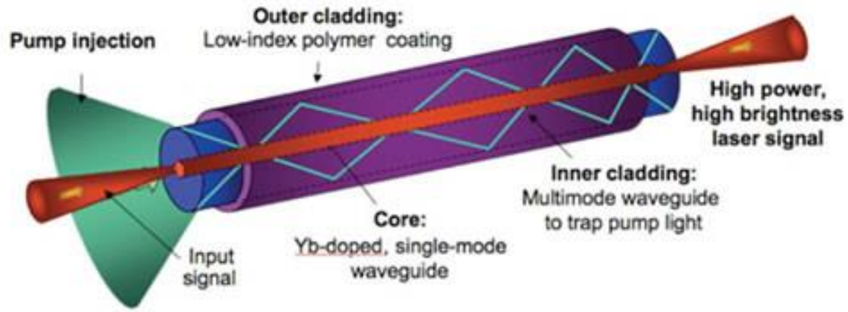




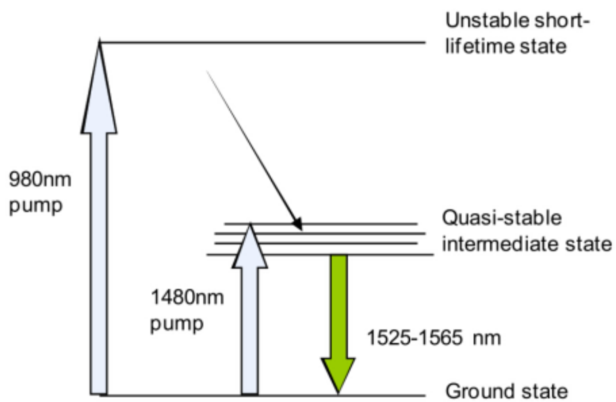
Laser tutorial

- How telecom lasers work
  - Semiconductor seed laser
  - Fiber based laser/amplifier:
    - Low brightness pump light – semiconductor laser
    - Absorption in core to amplifier signal to give high brightness output

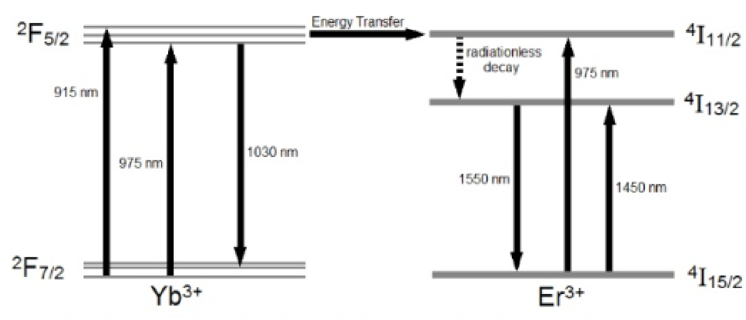




Erbium doped glass energy diagram



Erbium-Ytterbium co-doped fiber energy diagram



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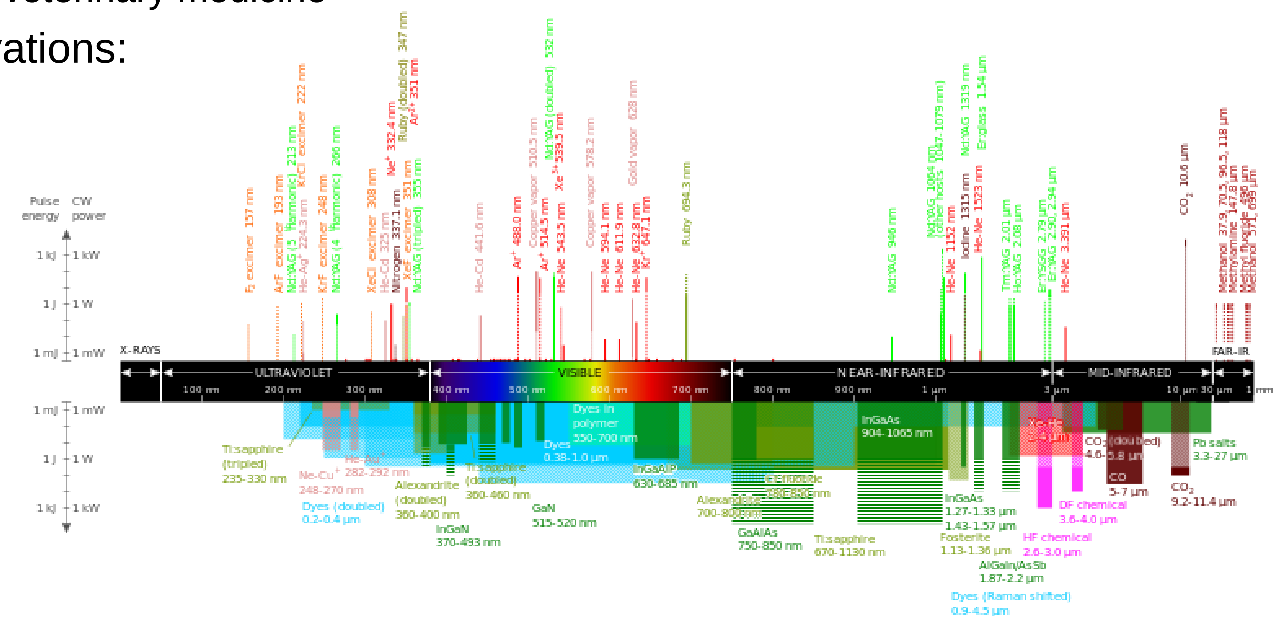
Laser Applications

- Medical:
  - dermatology: removing tattoos, hair, tumors
  - ophthalmology: lens repair, reattaching a damaged retina
  - oncology: treating cancer through photodynamic therapy, diagnosing tumors
  - surgery, dentistry, veterinary medicine
- Astronomical Observations:
  - Laser guide stars
- Science:
  - Atom cooling
  - Time transfer
- Machining, welding
- Directed energy
- Power beaming
- Remote sensing
- Ranging, lidar
- Entertainment – laser light shows
- Telecommunications:
  - Underwater
  - Fiber based
  - Free space



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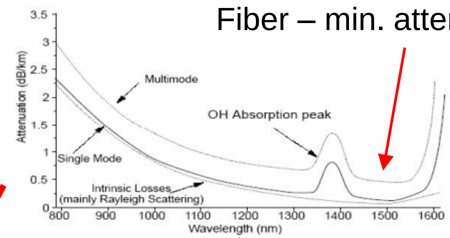
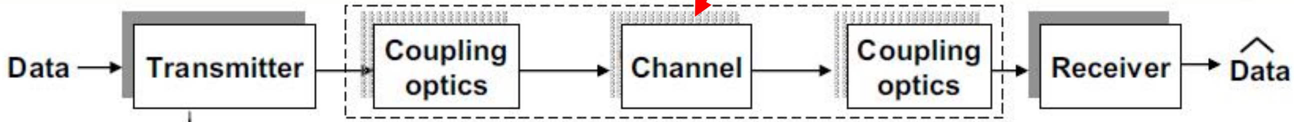
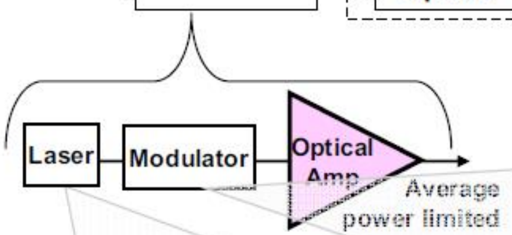
Lasers for Telecommunication

Fiber – min. attenuation of silica at 1.5 µm

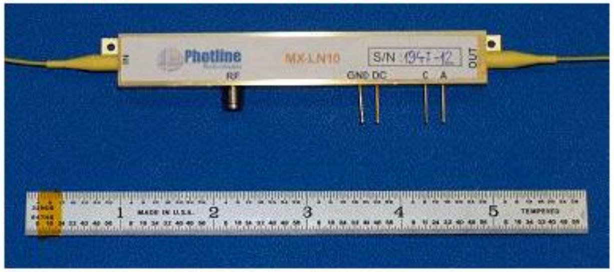






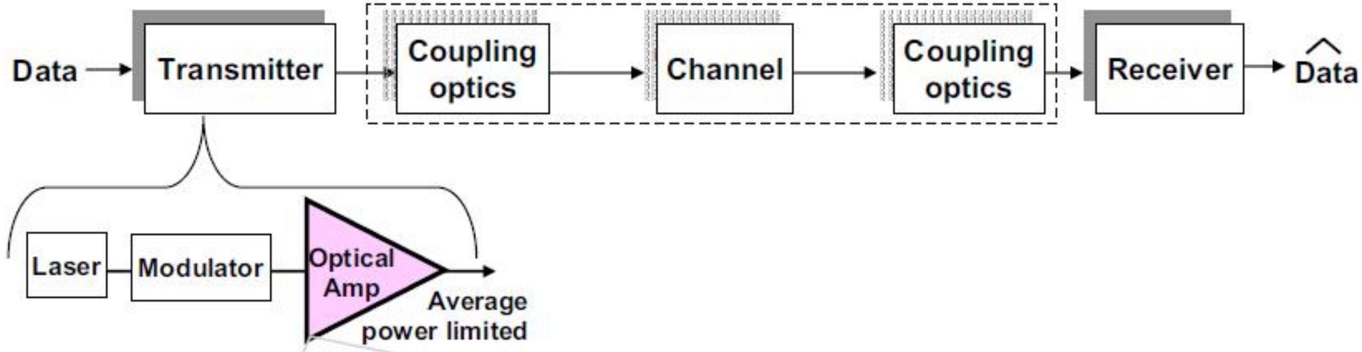
- **Laser (master) oscillators**
  - Distributed feedback (DFB) laser diodes
  - Narrow spectrum, controlled wavelength

- **Modulation**
  - Directly modulated laser (~2.5 Gbps)
  - External
    - Electro-absorption modulator (40 Gbps)
    - Mach-Zehnder modulator (40 Gbps)
  - Intensity and phase modulation formats
  - Large drive power, several Watts
  - More complex, requires stabilization



Courtesy MIT/LL

Lasers for Telecommunication



- **Erbium-doped fiber amplifiers (EDFAs)**
  - Power up to 20 W average
  - High gain up to ~50 dB
  - Wall plug efficiency up to ~15%

Courtesy MIT/LL

Lasers for Telecommunication

Transmitter Amplifier Characteristics

- High Power and Efficiency
- High Gain
  - Saturates easily, output power insensitive to dynamic range of input fluctuations
  - Extracts maximum power over wide range of input powers
  - Stable output power
    - Enables variable duty-cycle pulse position modulation (PPM) format
- Single spatial and polarization mode
  - Efficient power delivery in the far field
  - Background light discrimination
  - Less amplified spontaneous emission noise transmitted

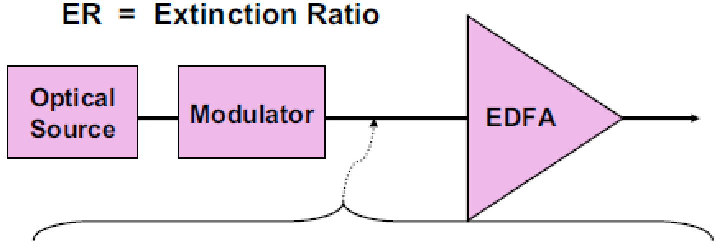
Laser Modulation Performance

Variable Duty Cycle Signaling Scheme

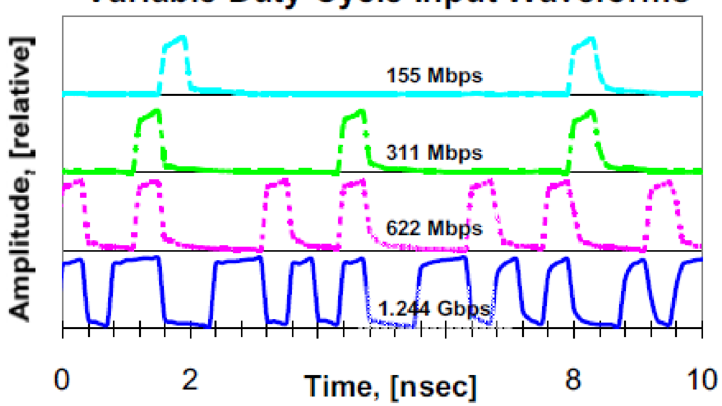
Average Power Limited (APL) Transmitter

$$\text{Peak Power} = \frac{\text{Average Power}}{[DC + ER(1-DC)]}$$

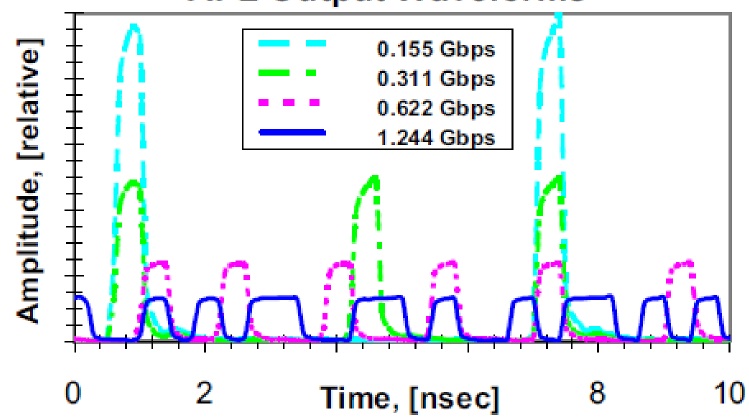
DC = Duty Cycle
ER = Extinction Ratio



Variable Duty Cycle Input Waveforms



APL Output Waveforms



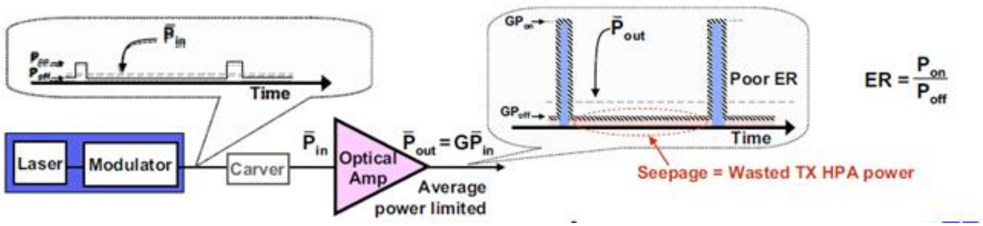
- No transmit power penalty
  - Constant average power at all rates
  - Peak power increases with reduction in data rate
- Variable duty-cycle PPM simplifies receiver
  - Single optical prefilter matched to highest data rate used for all data rates
- No receiver sensitivity penalty at lower data rates

Courtesy MIT/LL

Lasers for Telecommunication

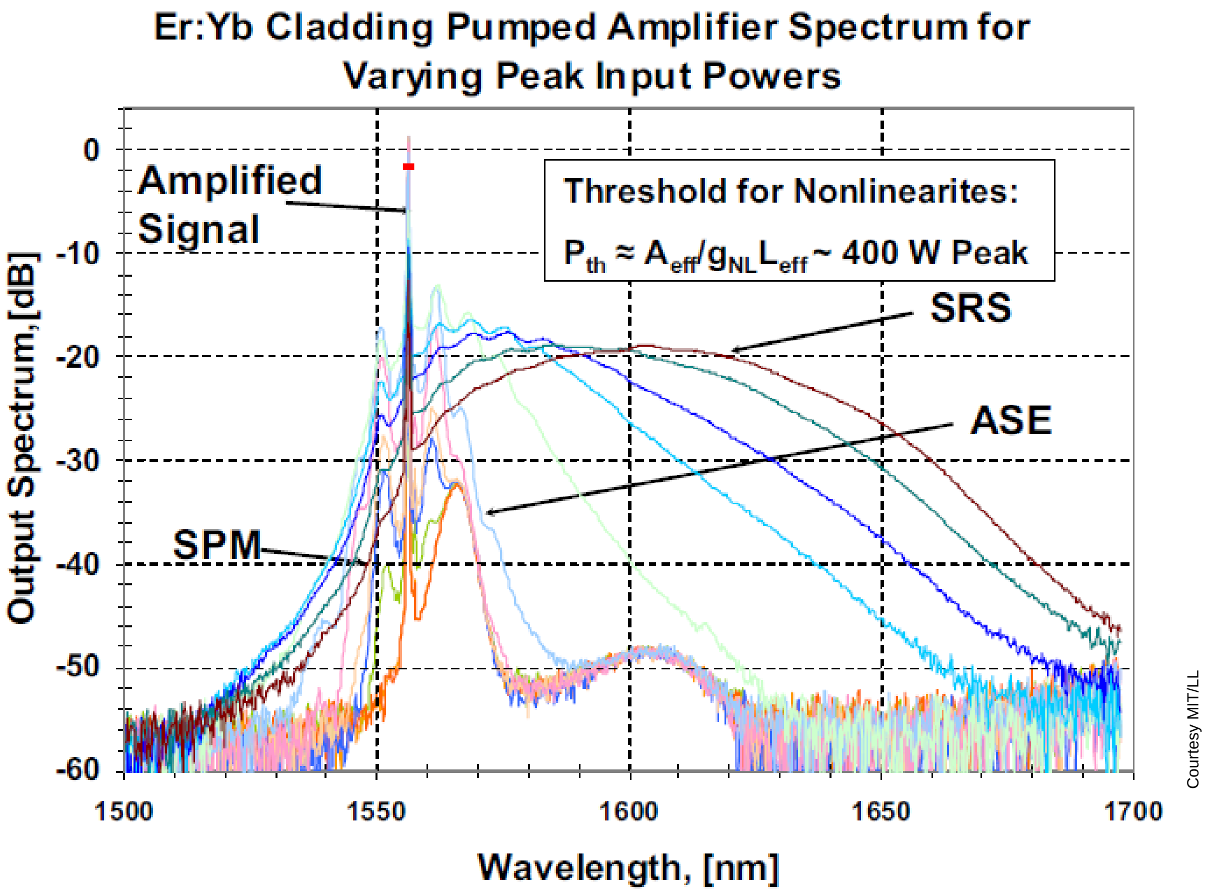
Transmitter Limiting Factors

- Transmitter power efficiency: saturated dynamic range of output
- Transmitter modulation extinction ratio (ER)
  - Low ER:



    - Reduces signal power and degrades bit error rate (BER)
    - Increases intra-symbol interference for intensity modulation
  - Optical modulators require active control to maintain ER
- Transmitter fiber nonlinearities scatter or shift signal out of band
  - Stimulated Raman Scattering (SRS)
  - Self Phase Modulation (SPM)
  - Stimulated Brillouin Scattering (SBS)
  - Four Wave Mixing (FWM)
    - SBS can be mitigated by broadening the signal spectrum or linewidth
    - SRS has higher threshold for occurrence
  - Mitigate with large core fiber, reduce fiber lengths, increased doping

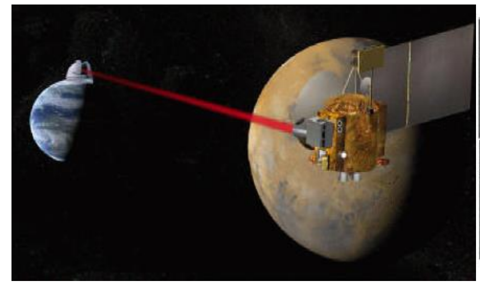
Transmitter Fiber Nonlinearities

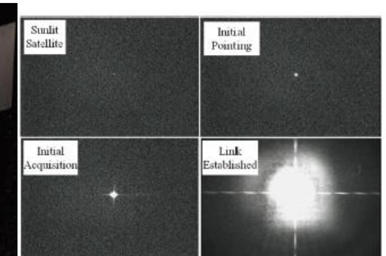


- Nonlinearity induced spectrum shifts usable signal power out of band

Lasers for Space Communications

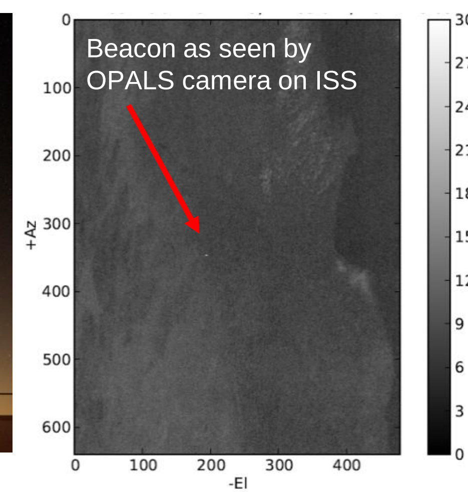
- Downlink laser
  - Deliver science data
  - High data rate
  - Wavelength and signaling compatible with photon counting receivers
  - Robust, compact and power efficient design
  - Leverage high reliability components





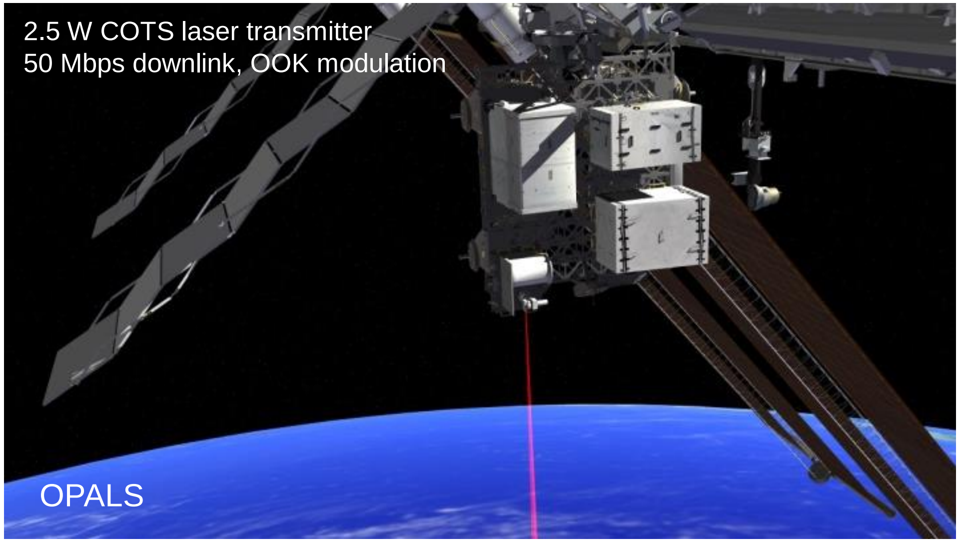
Downlink Laser:
Seen on ground (OTOOLE)

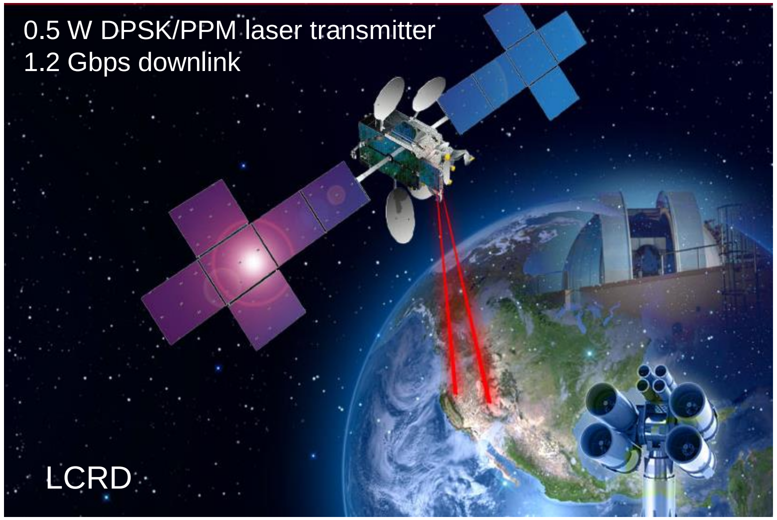
- Uplink laser
  - Beacon reference for spacecraft pointing, acquisition and tracking
  - High power with good beam quality
  - Uplink telemetry channel
  - Compatible with photon counting receivers
  - Leverage industrial applications

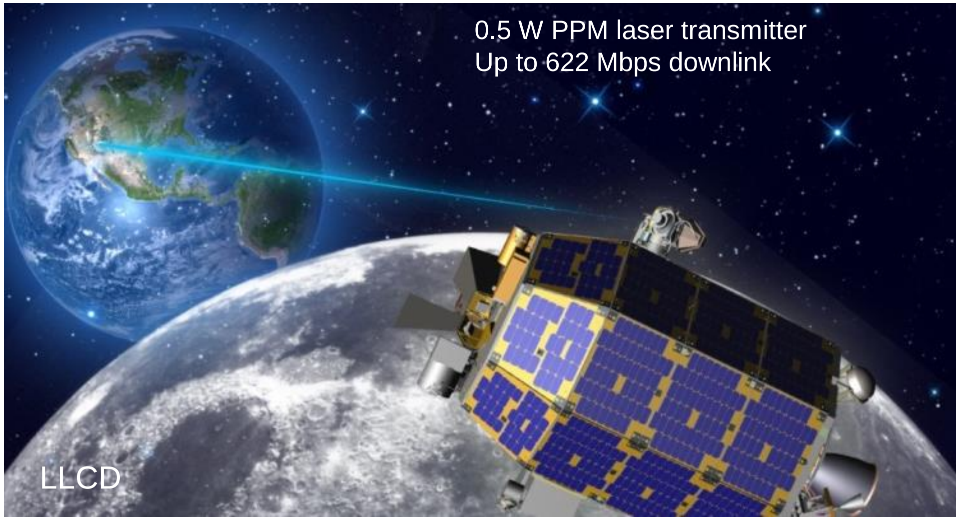


Uplink Laser:
Seen from space (OPALS)

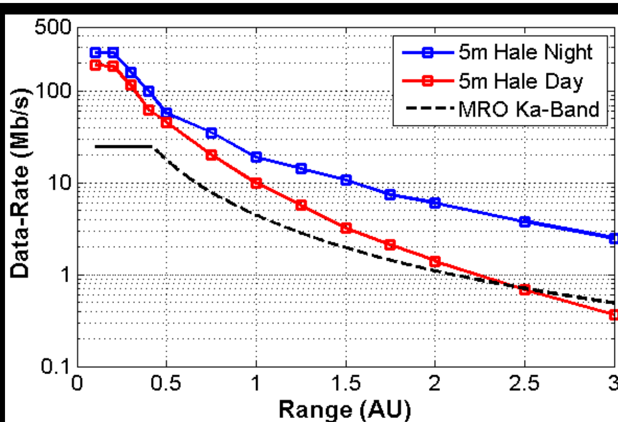
JPL Laser Communication Demonstrations



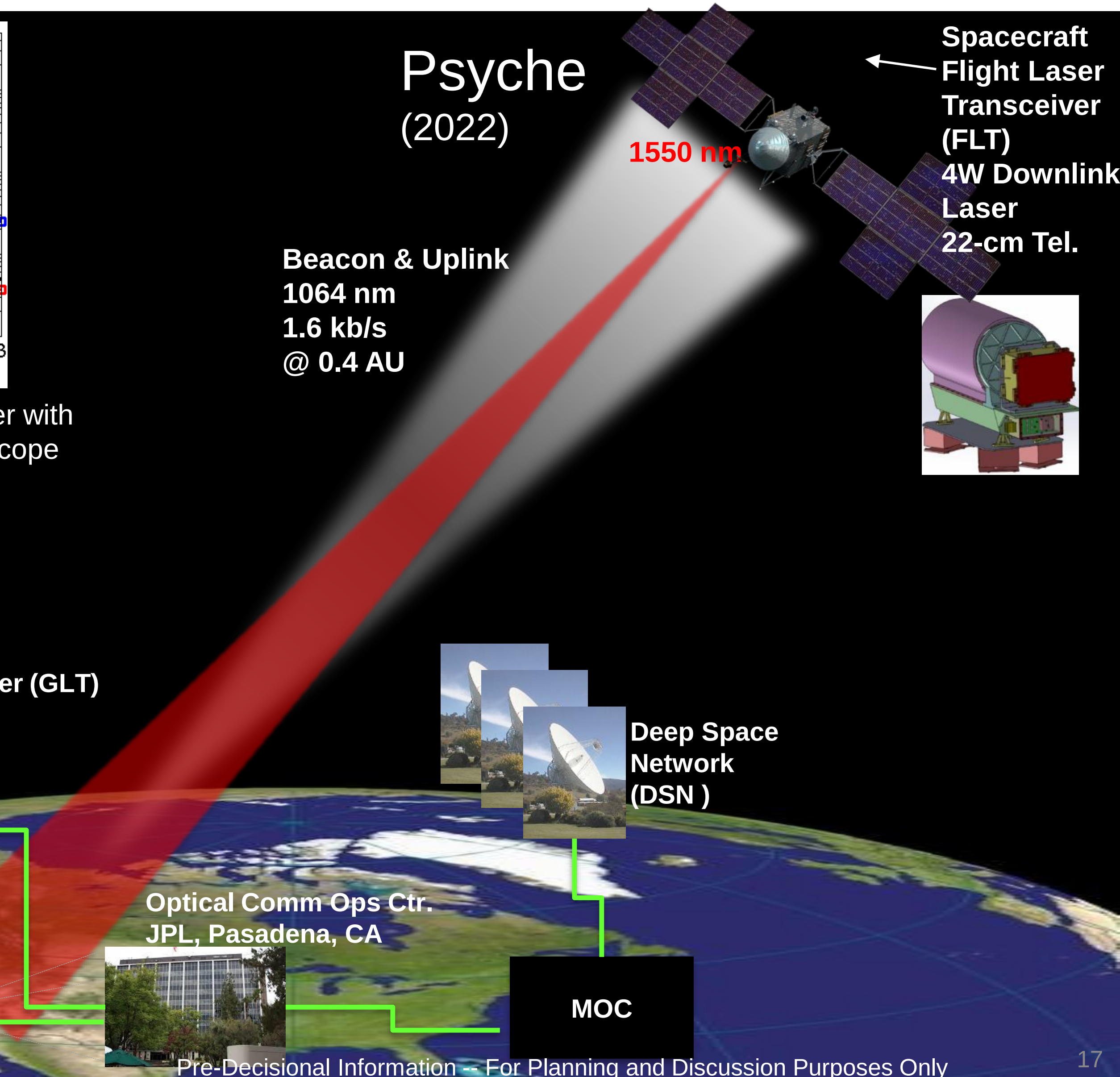




Deep-Space Optical Communications (DSOC)



Performance using 4W average laser power with 22 cm flight transceiver to 5m ground telescope



Lasers in Space Comparison

How different are lasers used for deep space compared to near earth?

Class	Mission	Distance (km)		Max. Laser Power (W) P_{avg}	P_{peak}	Data Rate (Mb/s)	Wavelength (nm)
LEO	OTOOLE (2009)	400-1000	Downlink	0.080	0.160	50	847
			Uplink	0.030	0.060 (comm) 4 (beacon)	2	819 801
LEO	OPALS (2014-16)	400-1000	Downlink	2	4	50†	1550
			Uplink	10	-	cw	976
GEO	LCRD (2019)	40,000	Downlink	0.5	8	1200	15XX
			Uplink	10	300 (comm) 20 (beacon)	1200	15XX
Lunar	LLCD (2013)	400,000	Downlink	0.5	8	622	15XX
			Uplink	40-60*	160*	20	15XX
Deep Space	DSOC (2022)	$(1 - 300) \times 10^6$	Downlink	4	640	267	1550
			Uplink	5000**	20,000**	0.002	1064

† > Gbps demonstrated from LEO - NFIRE *Total from 4-6 lasers ** Total from 10 lasers

DSOC Downlink Laser

DSOC Downlink Laser

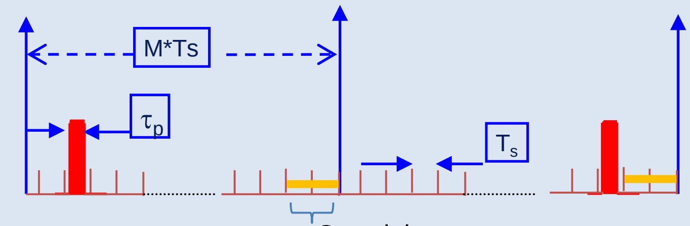
Key Performance Specifications

Parameter	Specifications
Wavelength (nm)	1550
Average Power (W)	4
Max. Peak Power (W)	640
PRF (MHz)	0.4 - 400
Modulation Format*	PPM 16 - 128
Pulse width Slot size (ns)	0.5, 1, 2 ,4, 8
Line-width (nm)	< 0.05
Polarization	Linear
Polarization Extinction (PER)	> 17
Extinction Ratio (dB)	> 33
Mode Quality (M^2)	< 1.2
Pulse Energy Variation (%)	< 5
Wallplug Laser Efficiency (%)	> 10
Packaging, Reliability	Min. SWaP, redundant critical components, > 1 yr lifetime
Athermal Operation (°C)	0 – 50

* 25 % guard time

PPM Modulation Format

Transmitted Laser pulse train



τ_p - laser pulse width

T_s - slot-width

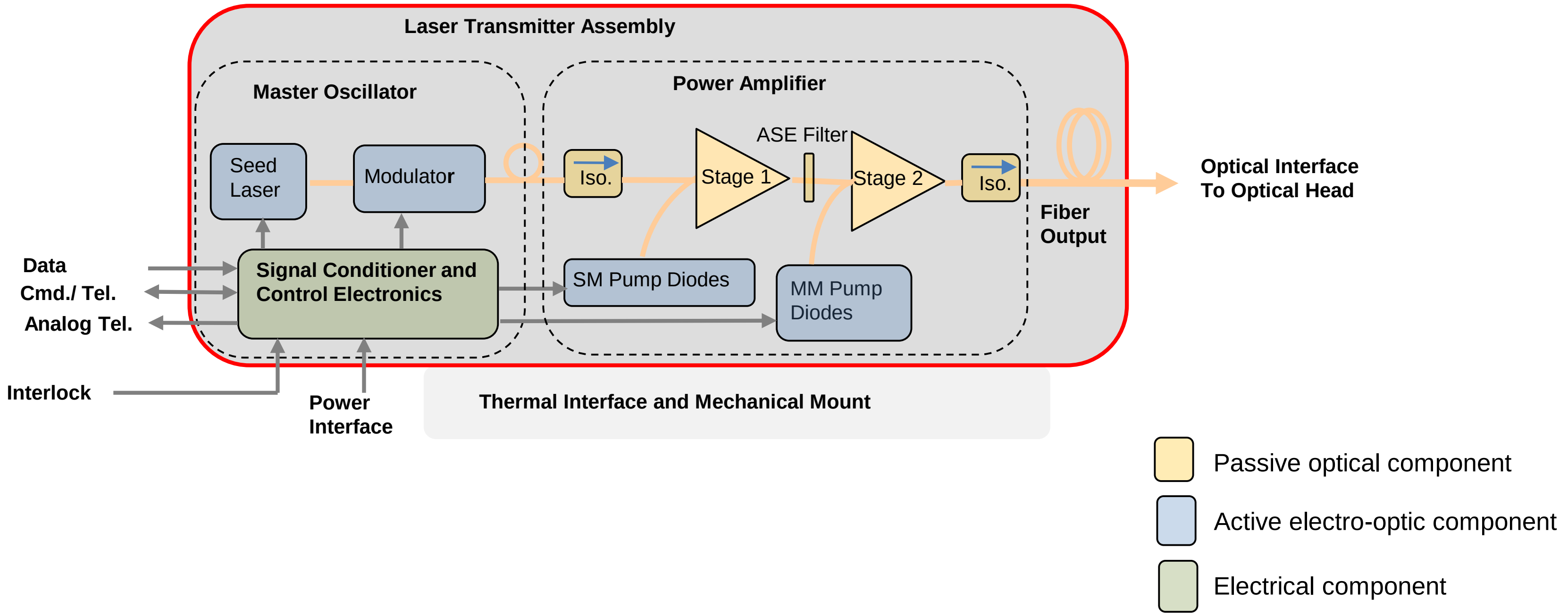
M - PPM alphabet size, 16-128

- Utilizes timing of pulse emission to transmit multiple bits of information per pulse
- By increasing M, the laser PRF is lowered (more energetic pulses) and channel capacity (bits per second) is traded for channel efficiency (bits/photon)

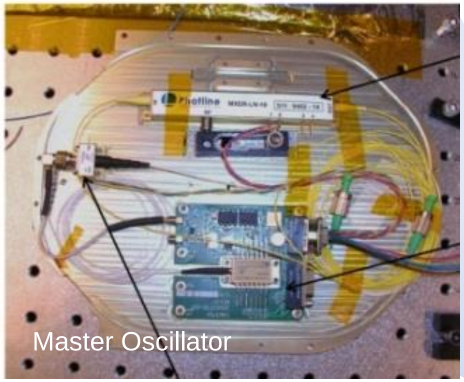
DSOC Downlink Laser Design

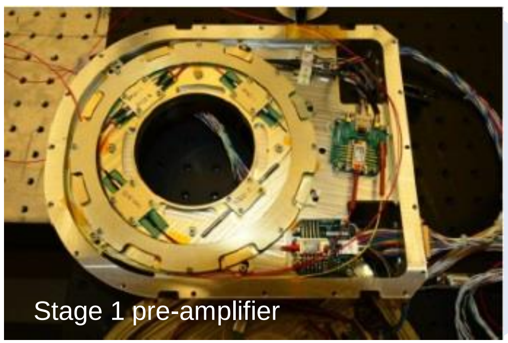
Master Oscillator Power Amplifier (MOPA)

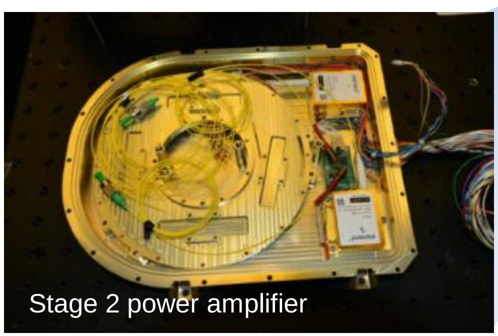
- Utilizes current fiber optic telecom based technology at 1550 nm
  - DFB seed laser, external E-O modulator for high pulse extinction ratio
  - Co-doped Er-Yb fiber amplifier using high reliability de-rated and redundant pump diodes, PM output
- High efficiency, high peak power
  - Non-linearity management with pulsed seed laser to increase linewidth (chirp), LMA fiber in final stage
  - Full telemetry for system monitoring – SBS, ASE, LOS

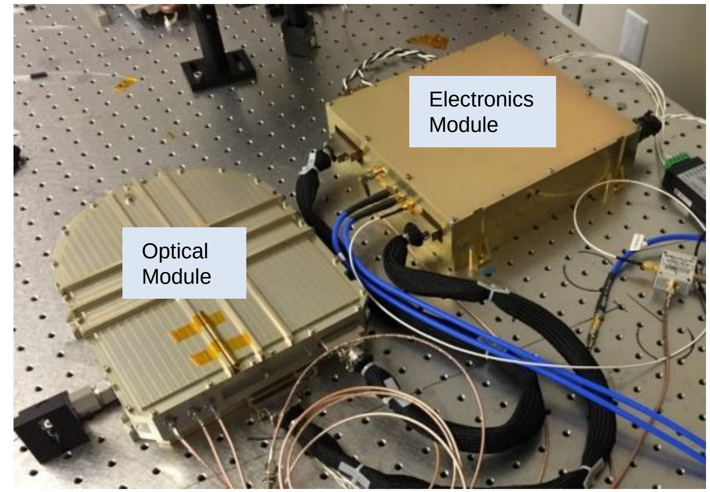


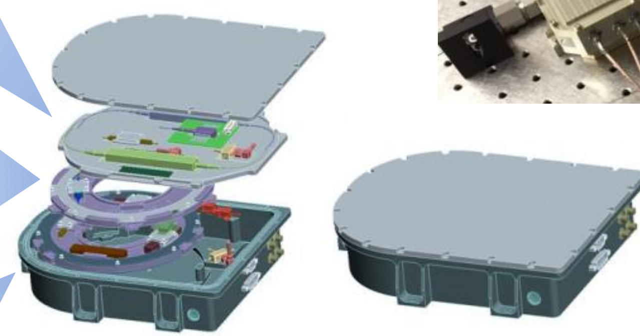
DSOC Downlink Laser Prototype

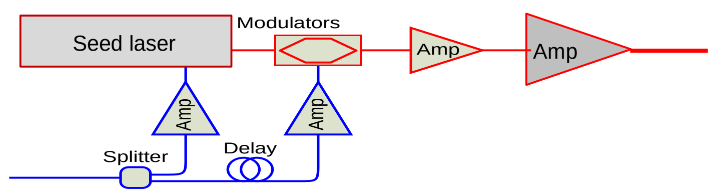








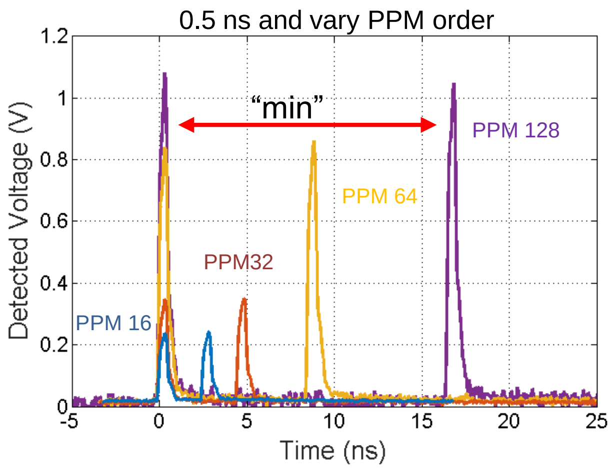


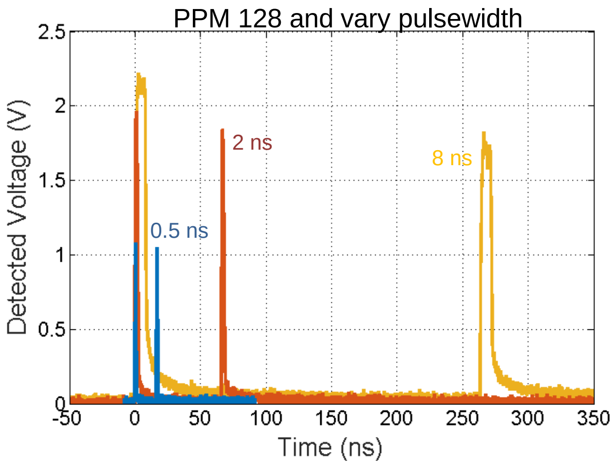


Courtesy of Fibertek

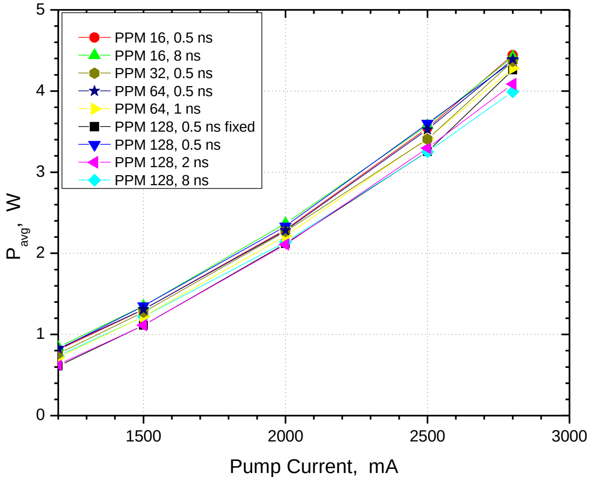
DSOC Downlink Laser Test Results

- **Pulse format**
  - PPM 16-128, 0.5 – 8 ns with min/max test pattern, ~ 4W

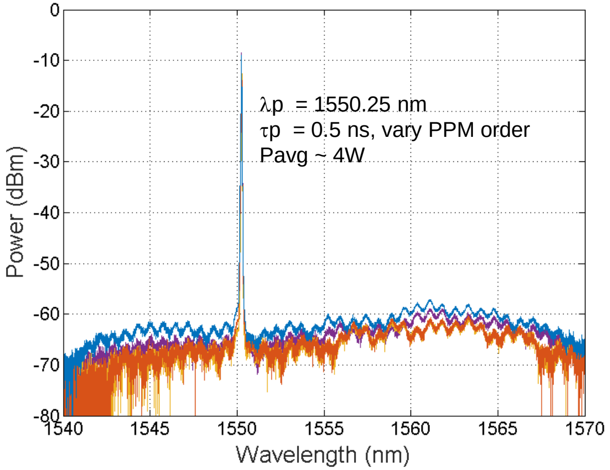




- **Output power**



- **Spectra**



Laser Component Qualification

Class D mission: Laser transmitter components qualification: up-screened Telcordia certified.

Comparison of Telcordia testing and NASA requirements.

Test	Telcordia Component (GR1221)	Telcordia Module (GR468)	NASA Requirement (GEVS)
Mechanical Shock	500 g, 5x/axis	500 g, 1 ms, 5 x/axis 300 g, 3 ms, 5 x/axis (< 0.2kg) 50 g, 11 ms, 5 x/axis (0.2-1kg)	10-4000 g*
Vibration	20-2,000 Hz, 20 g_{rms}, 4 x/axis	5-50 Hz 1.5 g, 50-500Hz, 3 g	20-2,000 Hz 20 g_{rms} (component) 14.1 g_{rms} (subsystem) 10 g_{rms} (workmanship)
Thermal Cycle (survival)	-40 to +70°C, 100 cycles	-40 to +70°C, 100 cycles	-10 to +55 ºC (controlled) -65 to +125 ºC (uncontrolled)
Lifetime	-	5000 hrs. at 85°C	Mission dependent

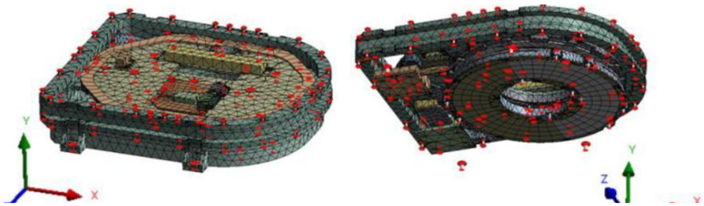
* frequency and payload dependent

What's needed:

Radiation tolerance, vacuum operation, pyroshock, system level environmental testing

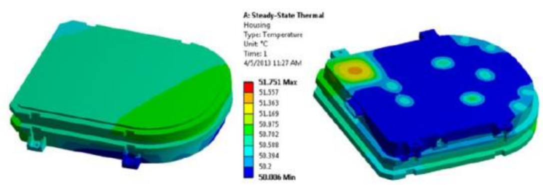
Environmental Analysis and Testing

Structural Analysis of Opto-Mechanical Design



Frequency (Hz)	ASD Level (g^2/Hz) Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

Thermal Analysis of Opto-Mechanical Design



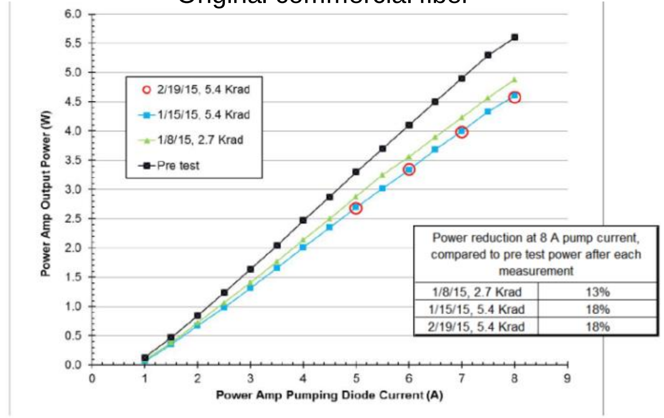
- Dominant heat-dissipating component is stage 2 pump diode
  - Mounted on baseplate near radiator

Extended “burn-in” under stress conditions

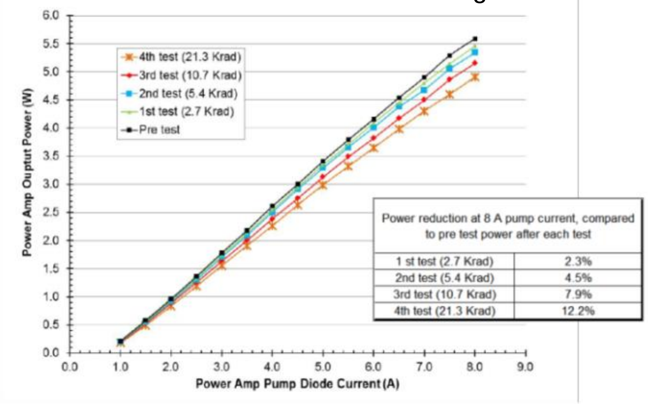
- 200 + hours TVAC reliability test passed

Radiation Test Results

Original commercial fiber



Radiation hardened fiber design



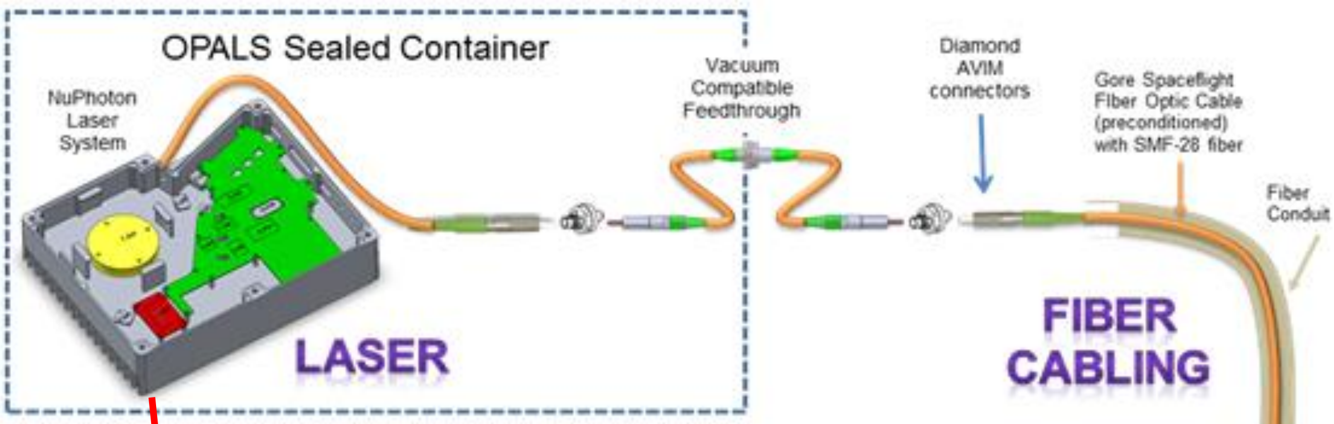
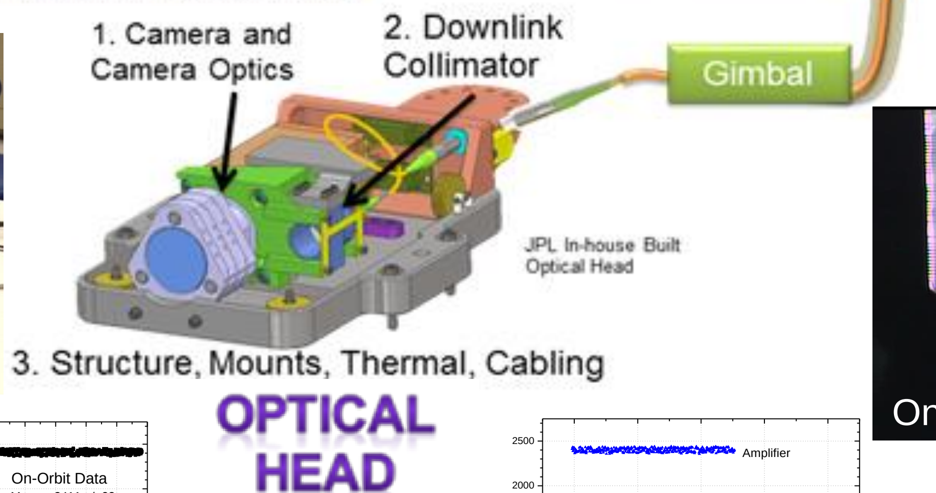
- Under accumulated dose of 5 krad (20krad with shielding) rad hard fiber has lower power loss - 4.5% compared to 18%.

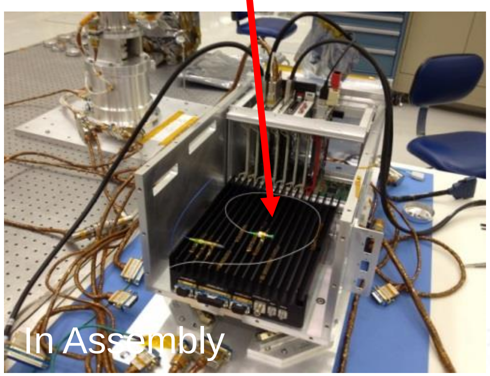
Performance demonstrated in environmentally qualified package

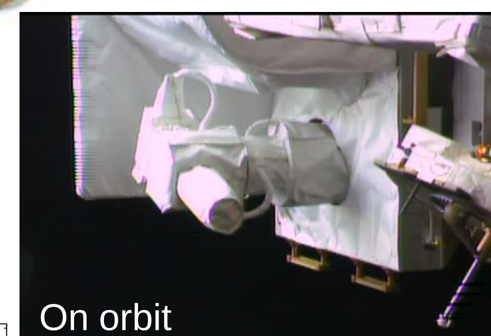
Courtesy of Fibertek

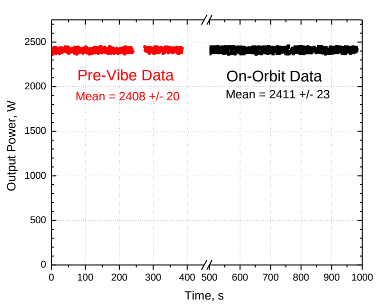
Example Laser Integration – OPALS

Configuration

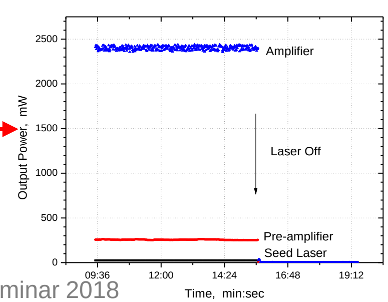









No degradation after 4 mon ops on orbit



DSOC Downlink Laser Risks

Things to be concerned about for lasers operating in space:

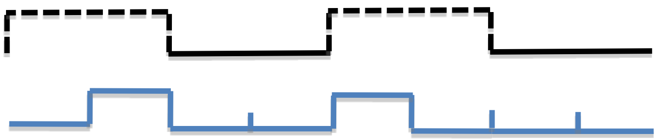
- Seed/pump laser packaging
  - Semiconductor bond wires
  - Hermiticity
  - Fiber alignment
- High power densities for pump laser diodes
- Optical feedback into fiber amplifier
- Radiation effects for optical fiber
- Data dropouts from electrical interface, transient gain spikes
- Cleanliness of fiber connectors
- But - no free space optical alignment

DSOC Uplink Laser

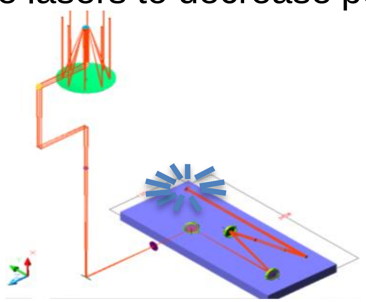
DSOC Uplink Laser Functional Description

- Multi-kW class average power to support beacon tracking and uplink comm. channel

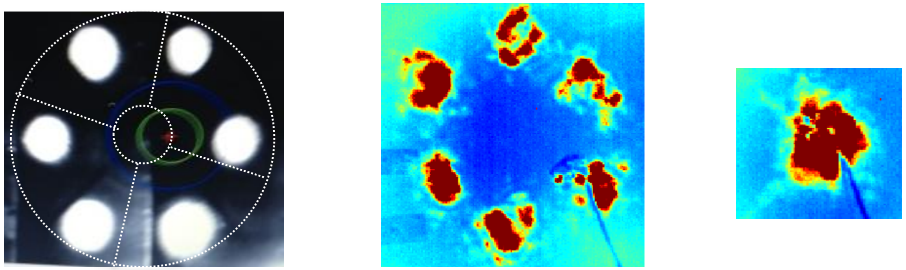
Uplink Signaling:



  - Multiple lasers to decrease power density on transmit optics and mitigate atmospheric effects



Uplink telescope Coudé path with multiple laser beams



Multiple uplink beams exiting telescope, at 1.6 km range and superimposed

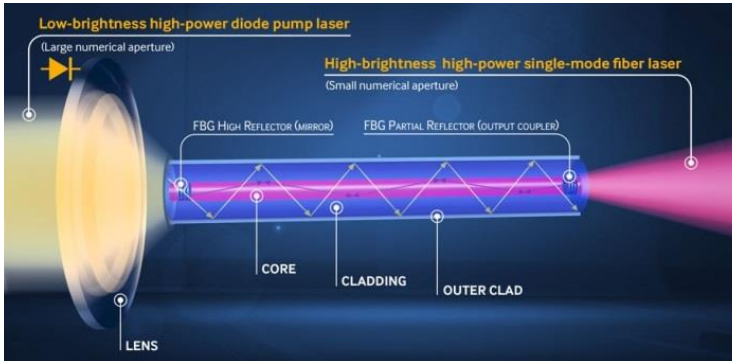
  - Baseline **500 W** per laser with 10 independent laser sources (plus 2 spares)
  - High peak to average power possible: $P_{peak} = m.P_{avg}$ for m-ary PPM

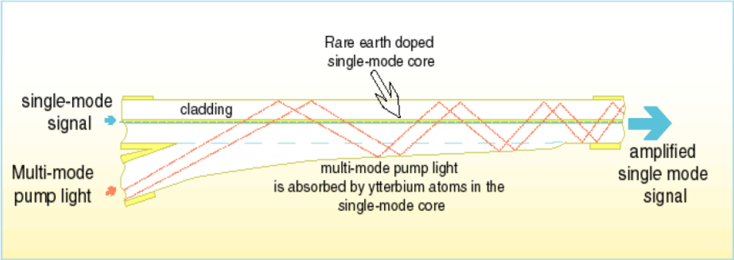
- Fiber based systems investigated due to robustness, low complexity and cost
  - Leverage high power commercial technology $\Rightarrow \lambda = 1064$ nm
  - Master Oscillator fiber Power Amplifier design
    - CW seed laser for narrow linewidth
    - Pulsed pump lasers for low rate modulation
  - ***Pulsed High power*** demonstrated in COTS industrial lasers but not with ***narrow linewidth***

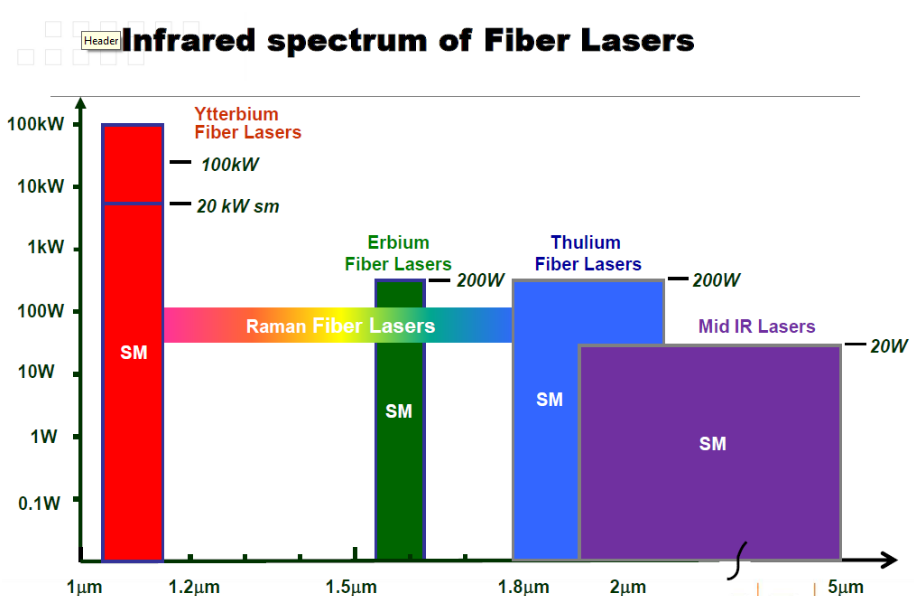
Commercial kW Class Fiber Lasers

High power fiber laser oscillators

- Fiber Bragg gratings integrated in fiber to form cavity
- High power, reliable broad area pump diodes
- Laser linewidth ~ 2 – 5 nm
- Single mode powers up to 100 kW have been demonstrated



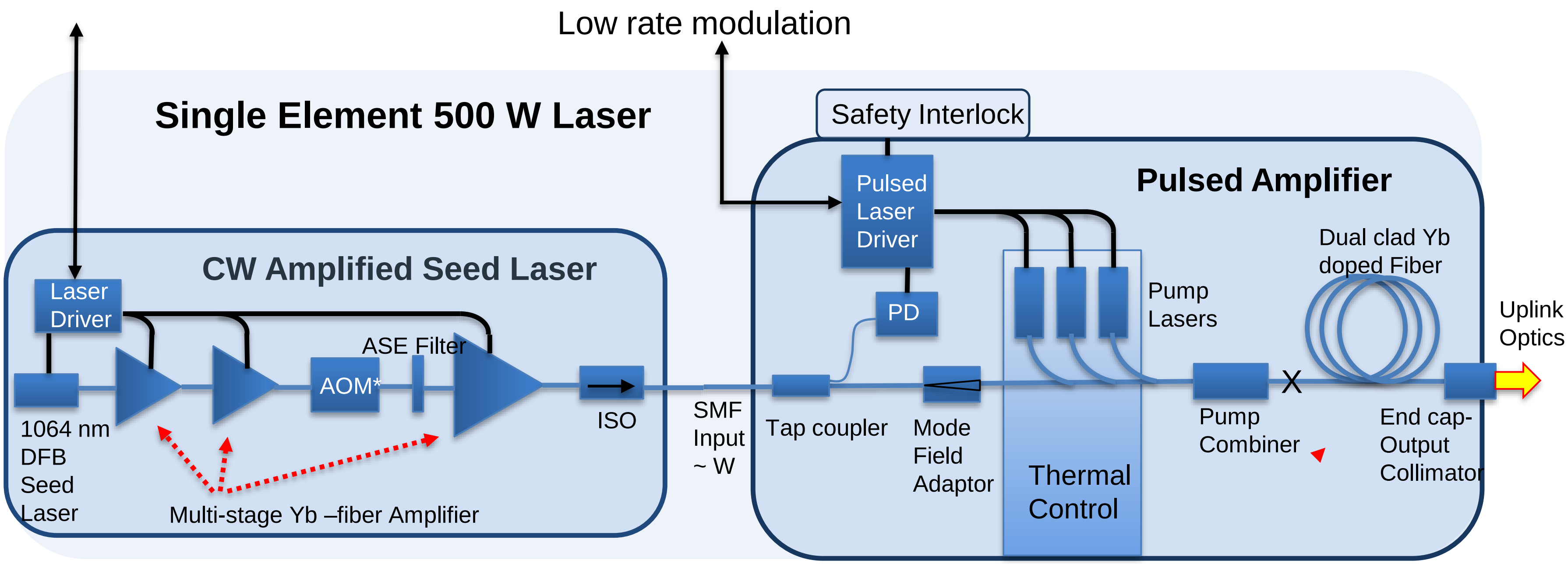




To get narrow linewidth kW class powers need design change to MOPA architecture

DSOC Uplink Laser Design

Parameter	Key Requirement
Average power, W	500 (5,000 total)
Modulation Scheme	B-PPM, 25 % DC
Pulse width, us	65
PRF, kHz	< 8
Wavelength, nm	1064
Linewidth, nm	< 0.2
Extinction Ratio, dB	> 13
Beam Quality, M^2	< 1.2

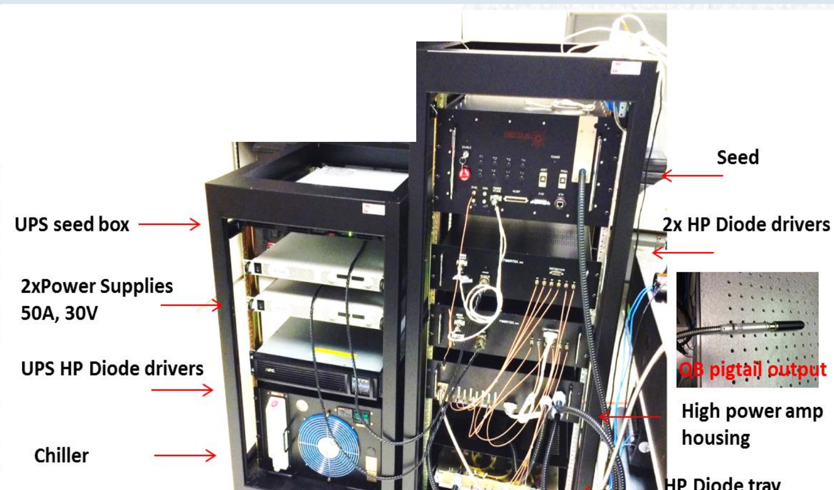


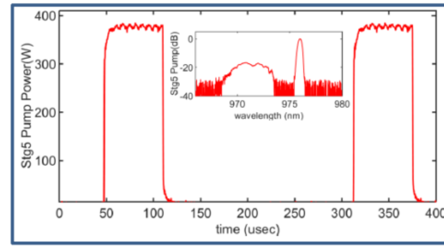
* If needed for short pulse operation

Uplink Laser Development

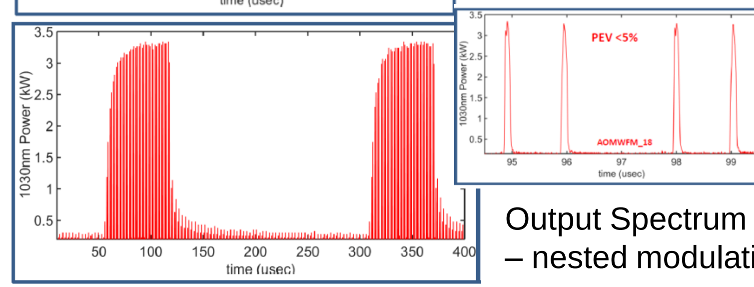
Dual Clad Yb Fiber Amplifier

- SBIR breadboard development
- Designed for short pulse modulation and 1030 nm
- High power demonstrated under modulation
  - P_{avg} = 500 W in free space beam coupled system
  - P_{avg} ~ 200 W in fiber based system, limited by fiber nonlinearities
- Good beam quality with LMA 30/400 um output fiber
- Narrow linewidth (0.2 nm) at low power only
- High wall-plug efficiency ~ 15 %
- Pulse energy variation ~ 25%
- Random polarization
- Water cooling with 1.5 m delivery fiber

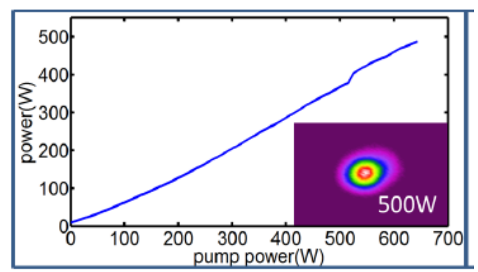




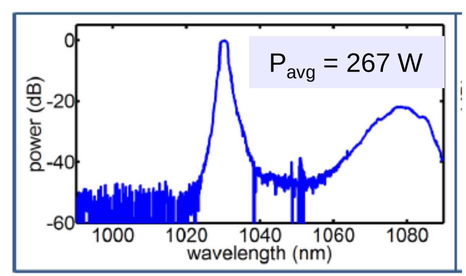
Pump Laser Modulation



Output Spectrum – nested modulation



Free Space Signal Output Power



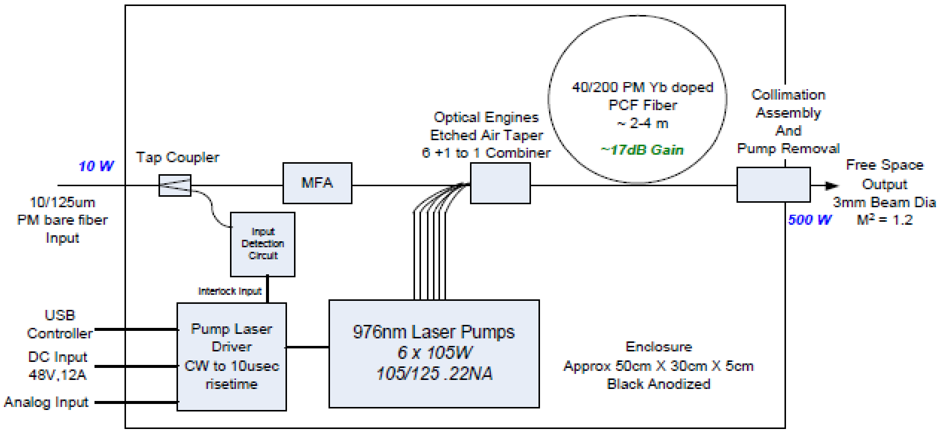
Log Spectral Output

Courtesy of Fibertek

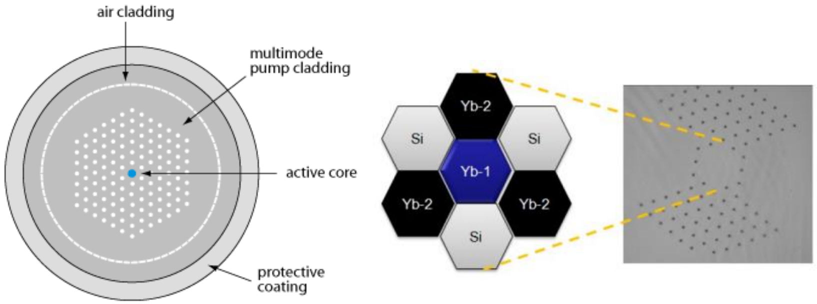
Uplink Laser Development

Jet Propulsion Laboratory
California Institute of Technology

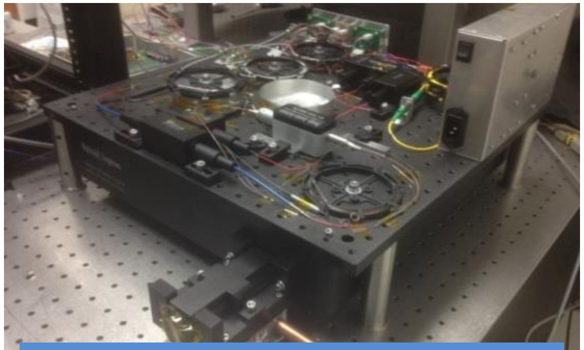
Photonic Crystal Fiber



- Increase mode size with tailored gain region
- Designed for short pulse modulation and 1030 nm
- Moderate power demonstrated under modulation
  - P_{avg} = 100 W limited by modal instabilities
  - Developed custom pump combiners
- Ongoing SBIR development
  - Goal of P_{avg} = 500 W with low rate modulation and ~ 25% duty cycle
- Water cooling with free space output

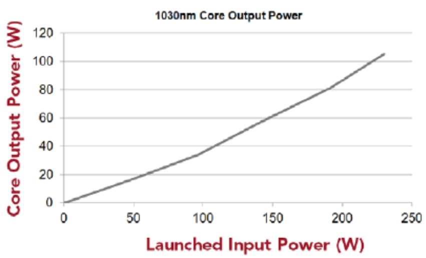


Gain tailored 30/400 um PCF Geometry



PCF Amplifier – 1030 nm, 100 W, 2 kHz

- 100 kHz, 200nsec exponential shape with bias
- 20m 40/500 PCF, 95% Pump Efficiency
- Output: 105W, 100ns, **1.05 mj,** ~50% Slope Eff.

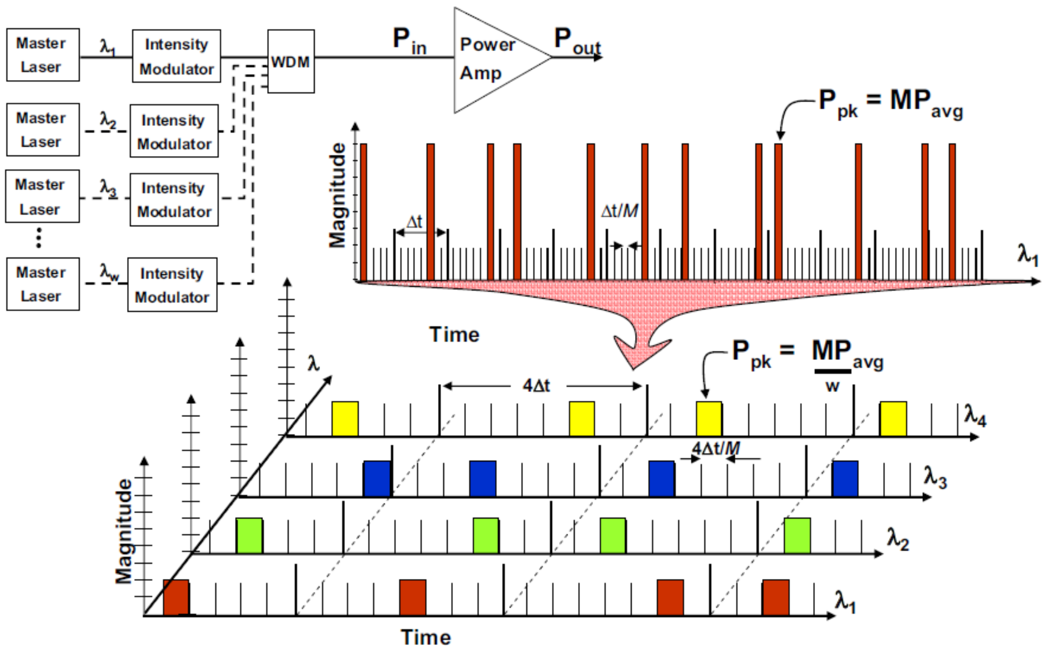


Courtesy of Optical Engines

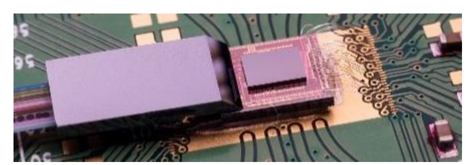
Future Work

Future Downlink Laser Development

- Multi-wavelength high power transmitter



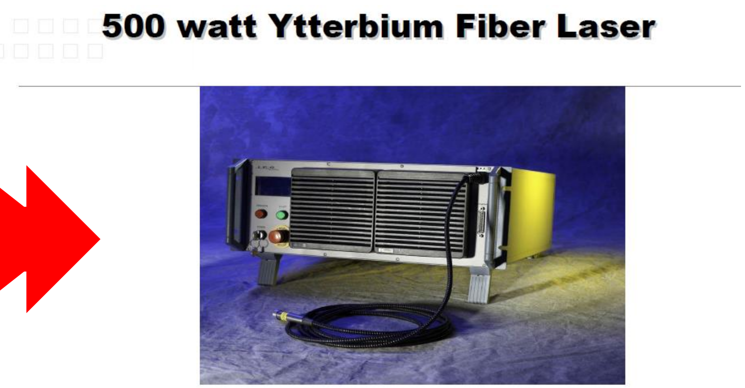
  - Reduces the electronics BW bottleneck
    - Allows increased data rate
  - Decreases the peak power in each channel: $P_{pk} = M P_{avg}/w$
  - Need to ensure different wavelengths do not overlap in time
  - > 50 W average power downlink laser transmitter demonstrated with 8 channels
    - Supports high (100 Mbps) data rates from ~ 2.6 AU.
- Compact, high efficiency transmitter
  - Photonic Integrated Circuits
  - LEO network constellation of satellites



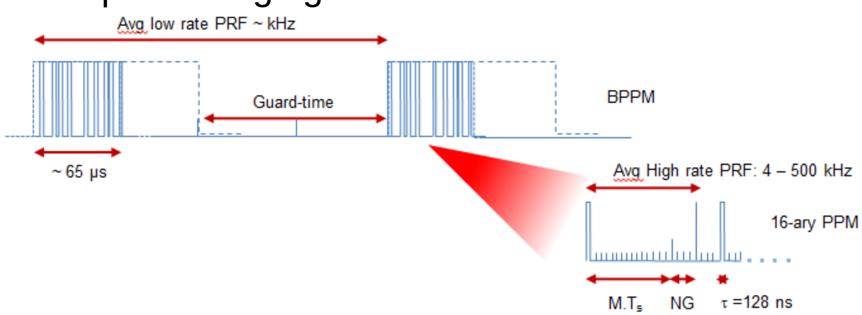
Jet Propulsion Laboratory
California Institute of Technology

Future Uplink Laser Development

- Compact, reliable high power fiber laser transmitter with narrow linewidth



- Nested high rate modulation scheme
  - Inner high rate modulation (PPM8 + 4) for comm: τ_s = 128 ns, data rate: 2.9 – 368 kbps
  - Outer low rate modulation for acquisition: 65 µs slot, 2 kbps
  - High peak power
  - Allows high resolution optical ranging



DSOC Lasers Summary

- Laser transmitters being developed for Psyche Mission to demonstrate deep space optical communications from > 1 AU
- Downlink laser transmitter has been developed to meet specifications in robust package
  - Multi-Watt average power and high peak power fiber based MOPA with narrow linewidth that leverages telecommunications technology
- Uplink lasers required for beacon reference and low rate commanding
  - kW class output powers with narrow linewidth under modulation

Acknowledgements

- The work of Fibertek and Optical Engines is gratefully acknowledged
- D. Caplan, M. Stevens, B. Robinson, ECOC 2009, “Free Space Laser Communications”

On to Psyche…..